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Energy loss of Cl^{q+} (52 MeV) through dilute H2 target: Evidence of non-linear term and non-Coulombian potential contribution

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Abstract

This report states about correlated charge and energy loss measurements in the collisional system Cl ions (1.5 Mev/u) in H_2. A windowless gaseous target with different thicknesses was used to measure simultaneously the charge state distributions (CSD) and the energy losses by the main populated outgoing charge states ($q = 12$–15). The Markov chain of the charge-changing process was deduced from a Monte-Carlo computation of the CSD evolution. The stopping cross-sections for individual charge states were finally deduced from energy loss data. Comparison of the experimental results with detailed calculations gives a clear evidence of relative importance of the individual contribution of non-linear correction terms and of the electron cloud bound to the projectiles. These two effects may be important for HI-ICF scenarios where a non-equilibrium charge state behavior is likely to occur.

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Keywords: Stopping power; Charge exchange; Energy losses; Inertial confinement fusion

0. Introduction

Theoretical determination of stopping power of a swift particle passing through the matter is a time-consuming and complex standing problem based on the works of Bohr [1] and Bethe [2]. For gas or solid targets, extensive databases [3] using semi empirical laws are available. Confidence on these predictions is ranging between few percents for light and/or fast ions and $\approx 10\%$ for partially stripped heavy particles. Therefore, practically, the numerous applications using fast particles as, for example, medical treatments or electronic hardness [4], weakly call theoretical predictions. This is not the case for plasma targets that have not devoted databases. Main reasons are the experimental difficulty to cross plasma and ion beams and the fast evolution of target characteristics induced by temperature. Consequently, applications such as HI-ICF are only supplied by theoretical calculations, which need dedicated experiments to be confirmed.

It is clearly established [5] that one of the main differences between hot and cold matters for swift heavy ion behaviors at the maximum of the stopping power is the strong modification of the charge changing cross-sections during the stopping process.

An accurate theory for stopping calculations, in the case of partially stripped ions, has to deal with non-Coulombian potential (nuclei Z surrounded by an electron cloud). On the other hand, for the velocity range concerning partially stripped ions, it has been proved that electronic processes responsible for the slowing down exhibit saturation as compared to first-order perturbation treatments [6]. These two effects (form factor and non-linear term) act like opposite contributions to the stopping cross-section and often with the same order of magnitude for the equilibrium charge state. As a consequence, usual stopping power measurements at the equilibrium charge state are not so useful to explore the individual contribution of non-linear term corrections and electron cloud because they concern only the sum of the two contributions. Their relative contribution is varying with the charge state. Experimental differential stopping cross-section correlated with the

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charge state, is then a unique way to address charge treatment in the stopping power theories.

1. Experiment

A detailed description of the experimental set-up devoted to ion–plasma experiments at Orsay has been reported in Refs. [8,9]. Briefly, a 52 Mev Cl^{13+} beam delivered by the Tandem Orsay facility interacts with a H_2 target. The gas cell is a quartz tube (52 cm long and 5 mm in diameter) enclosed between two fast valves, which insure a windowless interface with the vacuum of the beam line. The pressure range extends over 10 mbar with an absolute accuracy of 0.02 mbar. When the collimators start to be opened, we are able to monitor the evolution with time of the target thickness correlated to the gas expansion into the beam line vacuum. This was achieved using the energy loss measurement of a short beam burst (5 μs) exploring step-by-step the operating sequence of the valve (~5 ms) [7]. Absolute target thickness at the measurement time is then deduced with an uncertainty near 5%. Taking advantage of an original method using ions beams [8], the target purity was checked to be high enough (few 10^{-4} pollution is due to water desorption) to not trouble the energy loss analysis. Simultaneous measurements of the change state distribution (CSD) and energy loss for all the individual outgoing charge states were achieved with a large acceptance magnetic spectrometer [9]. The focal plane was equipped with a 1 m long plastic scintillator facing an intensified CCD camera. The emitted light intensity by each spot corresponding to the different outgoing charge state was checked to be proportional to the number of impacting ions, while position of these spots in the focal plane gives the energy of these ions with a measured accuracy of about few 10's of keV [10].

2. Experimental results and analysis

In Fig. 1, we show the relative charge state yield vs. the target thickness. Mean equilibrium charge state was found to be $\langle Q \rangle = 13.0 \pm 0.1$. It is reached for a target thickness of $\approx 10^{19}\,H_2/cm^2$. Fig. 2 displays the relative energy losses for the five main outgoing charge states vs. the same target thickness. At small target thicknesses, the differences between energy losses for the different charge state increase linearly. This corresponds to single collision condition in the charge-changing processes as it can be seen in Fig. 1. For large thicknesses, charge states equilibrate and energy loss differences are constant.

A Monte-Carlo code was used to simulate the determinist slowing down process with respect to the stochastic nature of the charge-changing processes. CSD of Fig. 1 was used to adjust recombination and ionization cross-sections set. Errors on these quantities were found to be 15% (5% due to the target thickness, 5% due to the statistic and 5% due to the target purity fluctuations).

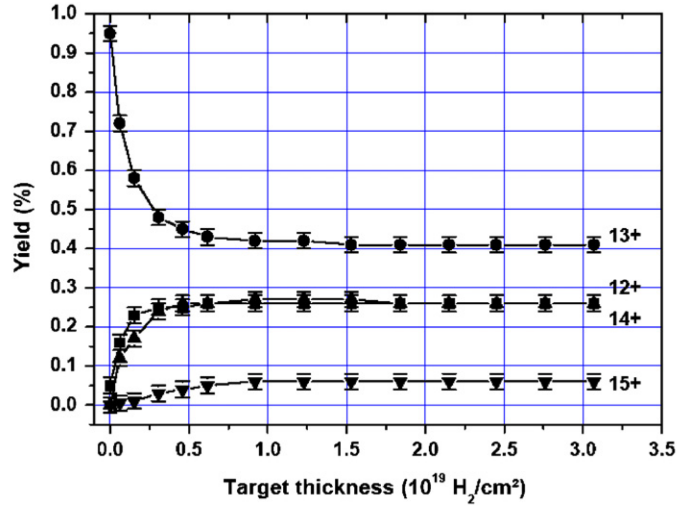

Fig. 1. Relative yield of the charge states for 52 MeV Cl ions vs. target thickness. The entrance charge is 13+.

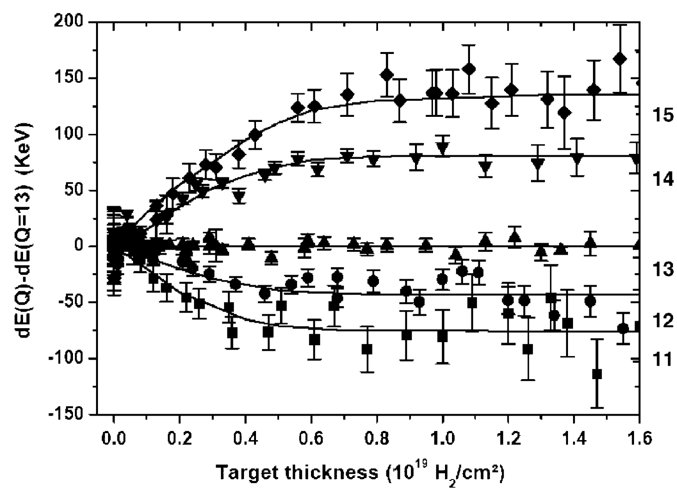

Fig. 2. Energy losses for the outgoing charge states as a function of the target thickness. Results are presented as the difference in keV with the 13+ charge state reference.

For each trajectory, using the Markov chain generated by the charge-changing processes, we computed the energy loss using stopping cross-section expressed as

$$S(Q) = \langle S \rangle (1 + (Q - \langle Q \rangle)\langle dS \rangle / \langle S \rangle) \quad (1)$$

where $\langle S \rangle$ is the stopping cross-section for the average charge state, $\langle Q \rangle$ is the average charge state and $\langle dS \rangle$ is the slope of the stopping cross section with the charge state.

X^2 minimization procedure taking into account every source of errors was then applied on data reported in Fig. 2, to get the experimental $S(Q)$ linear curve of Eq. (1). Reduced X^2 was found to be close to unity, showing [11] that a more detailed description of $S(Q)$ than a straight line was not relevant inside the errors on the experimental inputs (charge-changing cross-section, target thickness, target purity and energy loss measurements).